PROGRESS REPORT

NASA RESEARCH GRANT NSG-642

June 17, 1965 - December 17, 1965

The research effort on the theoretical development of a unified reaction theory and on its application to nuclear reactions is following the program outlined in the contract for this period. This research is directed by Professor William M. MacDonald and is being carried on by him and by Dr. William Beres as the research associate on the contract. Assisting Professor MacDonald and Dr. Beres are three research assistants, Mr. Aram Mekjian, Mr. Joseph Perez, and Mr. Diogenes de Oliveira. The work of Mr. Mekjian and Mr. Perez has been supported by funds provided under this contract. Mr. de Oliveira holds a fellowship from the Government of Brazil as a Fellow on leave from the Instituto de Fisica Teorica de Sao Paulo, Brazil.

The completed and current research is summarized below.

A. Single Nucleon Reactions

In the initial stages of the development of the unified reaction theory using shell model wave functions, the structure problem associated with the nucleus O^{16} was studied. Using the dispersion relations provided by the theory, the widths for nucleon emission and the associated level shifts of these states were calculated using wave functions for a square well potential. The widths resulting from the emission of both neutrons and protons to the ground and first excited states of O^{15} and N^{15} were evaluated. Although this analysis was considered preliminary, the agreement with the existing experimental data was sufficient to established the validity of the approach and justified further calculations.

In addition to this comparison between theory and experiment, the internal consistency of the theory was studied further. An approximation common to all shell model calculations is that the effective interaction is energy independent and local. Using a dispersion relation obtained from the theory, we were able to evaluate the energy dependence of the shell model interaction which is introduced by the coupling between the discrete shell model levels and the low lying continuum states. The very satisfactory result was found that the theoretical calculations are indeed consistent with the properties usually attributed to the effective interaction. [redacted]

A second very important, and somewhat related, approximation invariably made in shell model calculations is that the level shifts due to the interaction of the discrete and continuum states may be neglected. Again we were able to evaluate these shifts without additional approximations by using one of the dispersion relations found in the theory. It was established that these level shifts are indeed negligible compared to the widths of the associated nuclear levels. The satisfactory agreement of these preliminary calculations with experiment and the verification of their internal consistency indicated clearly the need and the justification for a more detailed study of this class of nuclear reaction and structure problems.

The previous calculations could not be considered complete for several important reasons. First, the use of a square well potential to construct the bound and continuum single particle states is subject to criticism on the grounds that the sharp cut off of the interaction at a certain radius is unrealistic. It is well known from optical model analyses of nucleon scattering that a more realistic interaction is provided by the Saxon-Woods potential, which goes smoothly to zero. The striking difference between these two potentials is seen in the penetration factors, which are proportional to the probability that an incident nucleon will be able to reach the interior of the nucleus. When the parameters of these two types of wells are adjusted to make them comparable, it is found that the penetration factor of the square well is both smaller and less energy dependent than that of the Saxon-Woods potential.

A second reason for extending these calculations is that the comparison of calculated and experimental widths of nuclear levels is not a very stringent or useful demand upon the theory. The extraction of the widths of levels from a reaction process is very uncertain when there exists a nonresonant background of somewhat indeterminate magnitude. In the case of the experimental data on O^{16}, the uncertainty is quoted experimental widths is estimated to be a factor of two or three. A much more satisfactory comparison can be made between the calculated theoretical cross section for a particular reaction and that which has been obtained experimentally. A number of experimental cross sections have been measured which involve the nucleus O^{16} as an intermediate state. The theoretical calculations of a number of these cross sections is quite feasible, although each is rather lengthy [redacted]

In the previous contract period Dr. William Beres initiated the more extended calculations indicated by the above considerations. For this calculation it has been necessary forrDr. Beres to carry out a further extensive theoretical development of the unified approach. Although general expressions had been derived for elastic and inelastic scattering and for photonuclear reactions, a considerable amount of effort is involved in reducing these general formulas to a form suitable for the evaluation of a reaction cross section. The complete reduction of the general expressions has now been carried out for both of these types of reactions, both for the calculation of differential and total cross sections.

The very necessary translation of the reduced theoretical expressions into a machine code which will enable one to carry out a complete unified calculation of a given reaction cross section in a matter of minutes is well underway. Sufficient flexibility will be provided as to make possible a detailed study of the effect of varying the shell model potential and the effective interaction. It is not possible to predict at this time the results of the final comparison with experiments. However, it is anticipated that the comparison will lead to very important conclusions about the extent to which the particle-hole states provide a complete description of the reaction amplitude in light nuclei. It is quite likely that the adulteration and displacement of these states by more complicated configurations will produce appreciable modification of reaction cross sections. In the event that this situation should obtain the currently held views of nuclear reactions in light nuclei will require some modification. We expect to study these effects quantitatively.

B. Foundation of Reaction Theory

The development of a more completely satisfactory theory of nuclear reactions using the techniques of many-body theory is being carried out by Professor MacDonald and Mr. Aram Mekjian. The advantages of this approach are the effects of renormalization and energy shifts of the target wave function, which are associated with the use of a completely symmetric unperturbed Hamiltonian, can be satisfactory handled. This approach also appears to be a very natural one for the particular description of nuclear resonances which is also the keystone of the unified theory of MacDonald. However, the development of a reaction theory using this formulism involves considerably more than the application of the existing techniques. A generalization of the existing many-body theory is in fact required in order to incorporate the new physical ideas contained in the unified reaction theory. Progress on this part of the research program has been very satisfactory and it is expected that it will be completed shortly.

From this new formulation which will incorporate the basic physical ideas of the unified theory, we expect to obtain an explicit equation for the shell model effective interaction which will permit its calculation from the free nucleon-nucleon potential. This is perhaps the central problem of nuclear physics at this time. We shall therefore devote our attention to this calculation.

C. Charge Exchange in Heavy Nuclei

The description of (p,n) reactions or charge exchange, resonances effects in heavy nuclei is being developed by Professor MacDonald and Mr. Joseph Perez. A complete description of these analogues state reactions which includes the fine structure due to complex levels has been given. This formulation is being compared with that given by D. Robson, which is based on the R-matrix theory of Wigner and Eisenbud. The theory of Robson was the first to be used to describe these reactions, and it has provided interesting results on the magnitude of the mixing of isobaric nuclear states. However, as generally seems to be the case with R-matrix analyses, the description appears to be somewhat labored. It is felt that the description provided by the unified theory has some advantages of simplicity and ease of calculation.

However, in neither the unified reaction theory nor the R-matrix theory is a completely satisfactory treatment given of isobaric spin states. This problem arises also in light nuclei where the complications introduced by a large neutron excess are now present. A case of particular interest can be studied, again in O^{16}, where shell model wave functions have been provided for the two isobaric spin states associated with $J=0^+$ levels in the giant resonance region. This appears to be one of the rare cases in which the isobaric mixing of state of a light nucleus is appreciable and it produces very important effects upon the nuclear cross section. It is also possible to analyze theoretically and in an unambigious fashion the contributions to the mixing. As a result of the calculations which already are being carried out on this nucleus, it will be also possible to quantitatively evaluate these effects and to carry out a comparison with experimental data. This work will make possible the extension of this analysis to the heavier nuclei in which the large neutron excess emphasizes some of the effects which are negligible in light nuclei.